

# The pulsation spectrum of VX Hydrae

M.R. Templeton<sup>1,2</sup>, G. Samolyk<sup>1,3</sup>, S. Dvorak<sup>1</sup>, R. Poklar<sup>1</sup>, N. Butterworth<sup>1</sup>, H. Gerner<sup>1</sup>

## ABSTRACT

We present the results of a two-year, multisite observing campaign investigating the high-amplitude  $\delta$  Scuti star VX Hydrae during the 2006 and 2007 observing seasons. The final data set consists of nearly 8500  $V$ -band observations spanning HJD 2453763.6 to 2454212.7 (2006 January 28 to 2007 April 22). Separate analyses of the two individual seasons of data yield 25 confidently-detected frequencies common to both data sets, of which two are pulsation modes, and the remaining 23 are Fourier harmonics or beat frequencies of these two modes. The 2006 data set had five additional frequencies with amplitudes less than 1.5 mmag, and the 2007 data had one additional frequency. Analysis of the full 2006-2007 data set yields 22 of the 25 frequencies found in the individual seasons of data. There are no significant peaks in the spectrum other than these between 0 and 60 c/d. The frequencies of the two main pulsation modes derived from the 2006 and 2007 observing seasons individually do not differ at the level of  $3\sigma$ , and thus we find no conclusive evidence for period change over the span of these observations. However, the amplitude of  $f_1 = 5.7898$  c/d changed significantly between the two seasons, while the amplitude of  $f_0 = 4.4765$  c/d remained constant; amplitudes of the Fourier harmonics and beat frequencies of  $f_1$  also changed. Similar behavior was seen in the 1950s, and it is clear that VX Hydrae undergoes significant amplitude changes over time.

*Subject headings:* stars: variables, stars: individual: VX Hya, stars: delta Scuti

## 1. Introduction

The high-amplitude  $\delta$  Scuti star VX Hya was discovered by Hoffmeister (1931), and subsequent observational work by Lause (1938) made clear that VX Hya was a complex pulsator.

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<sup>1</sup>AAVSO, 49 Bay State Road, Cambridge, MA 02138, United States

<sup>2</sup>email: matthewt@aavso.org

<sup>3</sup>email: gsamolyk@wi.rr.com

In the 1950’s and 1960’s Fitch (1966) conducted long-term *UBV* photometric monitoring of this star and found that changes occurred in the pulsation behavior on timescales of a year or less such that a single set of Fourier coefficients could not model the star over the long term. Fitch (1966) modeled VX Hya over these short time scales using a Fourier series consisting of two pulsation frequencies, the complete set of Fourier harmonics and beat frequencies through fourth-order, and a long period of about 4400 days. The physical origin of the long 4400-day period was not explained; it was used primarily to fit the data mathematically, and thus its reality is not certain. The underlying cause for the long-term complexity of VX Hya has remained unexplained to the present day.

The limited time-series observations published subsequent to the work of Fitch have not clarified the long-term pulsation changes, although both photometry and theoretical modeling seem to make clear that VX Hya is an otherwise normal  $\delta$  Scuti star. Strömgren photometry (Breger 1977) indicated that the star has near-solar abundances, and a mass over  $2M_{\odot}$ . The observed fundamental period and ratio of first overtone and fundamental periods agrees with stellar models computed using modern opacities and abundances; Templeton (2000) suggests the star is slightly more massive than 2.3-2.4  $M_{\odot}$  with solar-like abundances. The only apparent peculiarity is the long-term change in its pulsations, and long-term changes are no longer so peculiar among  $\delta$  Scuti stars. Both period and amplitude changes are observed in many other  $\delta$  Scuti stars (Handler et al. 2000; Arentoft et al. 2001; Breger 2003; Breger & Pamyatnykh 2006). However, the physical causes behind them remain unknown.

It is also unclear how these changes manifest themselves over time, primarily because the observational records for nearly all  $\delta$  Scuti stars are too sparse over the long term to give anything more than a snapshot of how a star might be behaving at that one epoch in time. For example, the existing data for most stars cannot show whether long-term period or amplitude changes are cyclical. A few stars, primarily high-amplitude stars whose time-of-maximum data are regularly collected, have long-term observational records, and period changes for those are reasonably well recorded. However, time-of-maximum data for multi-periodic stars are much harder to interpret (Zhou 2001; Klingenberg, Dvorak, & Robertson 2006). For these stars, a direct analysis of time-series photometry can provide a clearer picture of the long-term behavior, as well as provide a means to uncover as yet undetected variability.

In 2006 and 2007 a group of observers from the *American Association of Variable Star Observers* (AAVSO) undertook a campaign to intensively observe VX Hydrae’s complex light curve. Five observers obtained a combined 8498 *V*-band observations of this star during the two observing seasons, and the resulting light curves provide the best seasonal coverage of

this star to date. This light curve is an excellent data set from which to compute the current pulsation spectrum of VX Hydrae, and it provides a new baseline for comparison with both past and future data sets. In this work, we present a comprehensive analysis of these data. In Section 2 of this paper, we describe the observational data obtained and their reduction to a common system. In Section 3, we give full details of the time-series analysis and derivation of the Fourier spectrum and its changes from 2006 to 2007. In Section 4, we discuss the results of the analysis, and put this result in context of what is already known about VX Hydrae.

## 2. Data

The data set presented in this paper was collected by the five observers at five different locations: Florida, Wisconsin, Arizona, and west Texas in the United States, and Queensland in Australia. The observers all used telescopes with apertures of 0.2 to 0.25-meters, SBIG ST7 or ST9 series cameras, and standard Johnson (Bessell)  $V$  filters; see Table 1 for details. Approximately 8800  $V$ -band data points were obtained using TYC 5482-1347-1 (RA 09:45:29.56, Dec -11:58:45.8;  $V=11.577$ ,  $(B-V)=0.967$ ) as the comparison star. Following the removal of discrepant and overlapping data, the final light curve contains 8498 differential measurements taken over two seasons from HJD 2453763.63564 to 2454212.71478. These data were not extinction corrected or transformed to a standard system, but have all been placed on a common zero point. The lack of extinction correction may introduce a small nightly trend in the data, but absolute calibration is not required because any constant terms are removed during Fourier transformation. The photometric error per point varies by observer and by night, but typical values are on the order of 10 mmag or less.

Global coverage was obtained for a few nights during the 2006 season, with observers in both the US and Australia observing sequentially. Observers in the US typically did not overlap in coverage, but in cases where two sites observed at the same time the data with higher signal-to-noise was retained rather than averaging the two observers. The data for the 2006 season span 89 days, while those for 2007 span 122 days. More data were collected during 2006 with all five observers contributing observations during that season, and three contributing in 2007. The full light curve of VX Hya is shown in Figure 1, and the data from HJD 2453770 to 780 are shown in Figure 2 to highlight the data quality.

The light curve is clearly complex in nature, a signature of multiperiodic variability common in delta Scuti stars. VX Hya is a high-amplitude pulsator ( $\Delta(V) > 0.1$  mag; see Breger (2000) for a discussion of the classification), and so the variations are almost certainly due to radial rather than non-radial pulsation. (However, we note that non-radial pulsation

has been suggested for some high-amplitude stars; see Laney, Jøner, & Rodriguez (2003) for example). As we will show, the two mode frequencies and their frequency ratio strongly suggest purely radial double-mode pulsation with no other modes excited at amplitudes above the limits of the photometry (a few mmag). The complexity of the light curve will be shown to arise entirely from beating between these two modes.

### 3. Analysis

We Fourier analyzed the data using a deconvolving, iterative cleaning routine based upon the algorithm of Roberts, Lehar, & Dreher (1987). We performed very high resolution scans ( $\delta\nu \sim 10^{-6} - 10^{-5}$ ) between 0 and 60 cycles per day; the high resolution was required because the theoretical errors on the frequencies are much smaller than the  $1/T$  confusion limit. Over-resolving the Fourier transforms implicitly assumes there are no close frequency pairs with  $\Delta f < 1/T$ , which may or may not be valid but is a reasonable assumption for cases where rotational splitting of nonradial modes is not expected. For the Fourier analysis we also used a very small gain (0.05) with a large number of cleaning steps (12000) to keep the cleaning process as numerically smooth as possible.

We performed three different scans: one on the 2006 data alone, one on the 2007 data alone, and one on the combined 2006-2007 data set. After the spectra were computed, we then extracted the 200 highest-amplitude peaks from each spectrum, with 200 being an arbitrarily large number sufficient to detect all significant peaks and reach the noise level at high frequencies. To assess which if any of the resulting peaks were real we used the following selection criteria. First, we assumed that the two highest-amplitude peaks  $f_0$  and  $f_1$  were the two known pulsation modes. Next, any subsequent measured peak matching a beat frequency calculated using  $f_{\text{beat}} = if_0 + jf_1$ ,  $-10 \leq i, j \leq +10$  is considered real but only if it is significantly above the local noise level, it is present in Fourier analyses of each season's data analyzed by itself, and that the difference between the observed beat frequency and the predicted one is less than the statistical error on the observed frequency. Third, any additional peaks not matching a predicted beat frequency must also be significantly above the local noise level. For the noise limits, we did not calculate error bars from the spectra based on the local noise power, but instead assumed a global value based upon the limits of the data, and it is clear that the noise is frequency-dependent. At a frequency of 0 cycles per day, the  $3\sigma$  noise level is around 2-3 mmag, while it is less than 1 mmag at 40 cycles per day. However, using a global mean frequency did not significantly affect the results.

In Figures 3 and 4 we show the Fourier spectra for the 2006 and 2007 data sets, along with the spectra calculated following prewhitening with the initial set of frequencies selected

by the criteria above. Twenty-five frequencies were found independently in both the 2006 and 2007 data sets; their presence in each independent data set strongly suggests they are real. Five additional frequencies were unique to the 2006 data set, and one additional frequency was unique to the 2007 data set, all of which had Fourier amplitudes below 1.5 mmag. These peaks are questionable, but their frequencies match predicted Fourier harmonics or beat frequencies and are above the local noise level, and thus may be real. Twenty-two of the 25 frequencies also appear in the Fourier spectrum of the combined 2006-2007 data set.

At low frequencies, there appear to be peaks at 1 c/d and below which may be due to nightly extinction or sky brightness variations, or to observer-to-observer differences in system sensitivity. There are several additional peaks at frequencies below 15 c/d at the level of 1-2 mmag, all near the local (frequency-dependent) noise level. There are additional frequencies above 25-30 c/d which may be additional beat frequencies, but their amplitudes are extremely low, and are at the  $1\sigma$  uncertainty limit; they may well be real, but we opted not to include them among the confirmed peaks. No other statistically significant frequencies between 0 and 60 c/d were detected in the prewhitened spectra, suggesting that no other pulsation modes are present in these data with measurable amplitudes. In Table 2, we show the frequencies amplitudes, phases, and their identifications as derived from each of the two seasons' light curves. The  $1\sigma$  error bars on frequency, amplitude, and phase were calculated according to Lenz & Breger (2005).

#### 4. Discussion

There are several interesting things to note about these sets of frequencies. First, to reiterate, all of the peaks above are (a) well above the local noise limit, and (b) are identified as either Fourier harmonics of one of the pulsation modes, or are beat frequencies; there are no other statistically significant peaks in the spectrum. Thus we can conclude that VX Hya is only pulsating with two modes, at least at the present epoch. We are secure in the identification of each peak as a harmonic or beat, as they match periods calculated using integer combinations of the two mode frequencies to well within the frequency errors in each case. As further evidence of their reality, we show the harmonic amplitudes  $if(0)$  and  $jf(1)$  in Figure 5. The harmonic amplitudes for a given high-amplitude mode decrease exponentially with increasing harmonic order (see Jurcsik et al. (2005)), and it is clear from the log-linear graph that these amplitudes do indeed follow an exponential decay down to their detection limits. The amplitudes of beat frequencies having fixed  $i$  or  $j$  values exhibit the same exponential decay.

There is no evidence for additional pulsation modes with observable amplitudes in the

VX Hya light curve, suggesting that VX Hya is a pure double-mode pulsator. The observed ratio of the two primary mode frequencies  $f_0/f_1$  is 0.77316, which is typical of the ratio of the radial fundamental and first-overtone mode frequencies in high-amplitude  $\delta$  Scuti stars. Templeton (2000) showed that this ratio is consistent with a  $\delta$  Scuti star of near-solar abundances, having a mass  $> 2.4M_\odot$ . The pulsation frequencies shown in Table 2 are consistent with the results of Fitch (1966), who found that linear combinations of  $f_0$  and  $f_1$  up to 4th order were sufficient to model the light curve, with the exception of an unexplained long-term variation. Based upon the bulk of the pulsation behavior, VX Hya appears to be a normal high-amplitude, double-mode  $\delta$  Scuti star.

Second, we found no evidence for secular changes in frequencies from the Fourier analysis, but found strong evidence for a change in the amplitude of  $f(1)$  from 2006 to 2007. The frequencies of each matched peak do not differ by more than  $3\sigma$  from 2006 to 2007, and so the frequencies are constant to within the measurable errors. (We note that we have not yet analyzed the time-of-maximum information for these data which is more sensitive to period changes, and we encourage a careful  $O - C$  analysis using these data.) We have, however, detected a highly significant increase in amplitude of  $f_1$  between 2006 and 2007. The amplitude in 2006 was  $\Delta(V) = 0.1176 \pm 4$ , and in 2007 was  $\Delta(V) = 0.1272 \pm 7$ . This is a change of nearly 0.01 magnitude within 1 year. Such a rate of change maintained over long timescales would result in radically different pulsation spectra over time, making it difficult to measure or model the light curve with certainty. No recent photometry has been published but the amplitudes obtained by Fitch in the 1960’s were substantially different. Based upon this two-year set of observations alone, it appears that the amplitude of at least one of the pulsation modes of VX Hya is highly variable, and its variability would also impact the amplitudes of its Fourier harmonics and beat frequencies.

The sole question for VX Hya remains the long-term stability of its pulsation spectrum, and the origin of amplitude variation. Fitch (1966) showed that between 1955 and 1959, the best-fit amplitudes of the observed modes, harmonics and beat frequencies all vary, including  $f_0$ . The amplitudes of all modes detected in our data lie within the range of yearly mean amplitudes detected by Fitch, suggesting VX Hya’s pulsation behavior in the present epoch is relatively unchanged since the 1950s. Even if the individual component amplitudes are highly variable, they appear to remain within a well-constrained range. Fitch’s yearly mean amplitudes from 1955 to 1959 appear to show that the amplitude of  $f_1$  varies over a larger range than does  $f_0$ . The 450-day time span of our observations is too short to state whether the amplitude of  $f_0$  is genuinely constant in the long term; amplitude changes in single modes have been observed in other stars, but further observations may show that it too is changing over the long term.

It is possible that the temporal variations in VX Hya’s behavior are genuinely cyclical in nature as Fitch (1966) implied with the invocation of a 4400-day supercycle, and that the present set of observations are simply not sufficient to constrain the length and nature of this behavior. In principle, we could detect evidence of a cycle having a period of up to 225 days with our data, but we do not find any such period. Therefore, any cyclical variations must have longer periods than this.

We encourage future monitoring of VX Hya, including season-long campaigns that can investigate the changes in its pulsation behavior that may occur on long timescales. As we have shown, such campaigns can easily be done with small telescopes, and we encourage the organization of and participation in such campaigns by the Amateur, Professional, and Science Educator communities.

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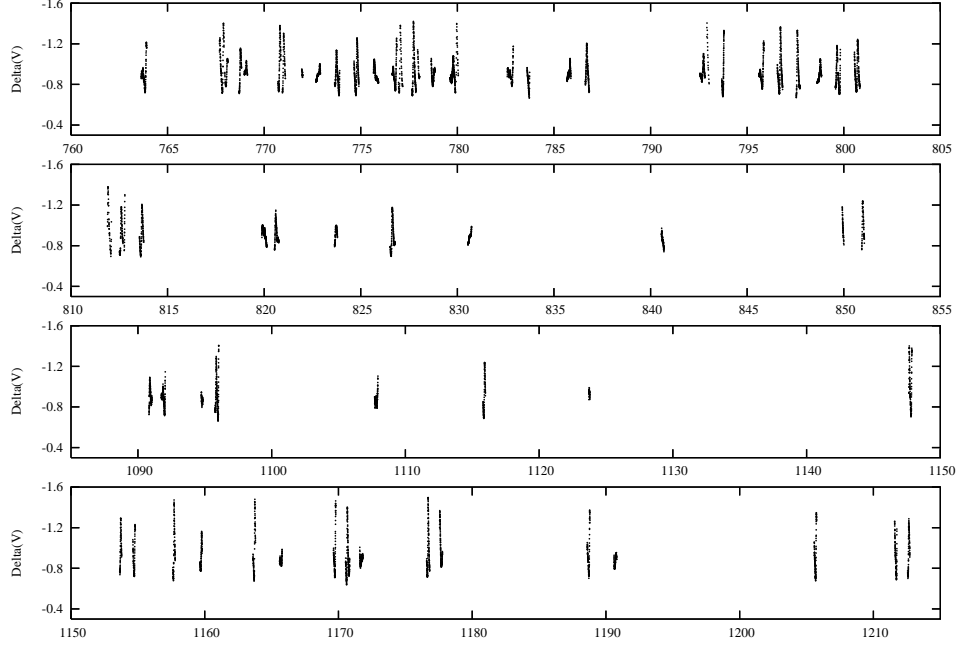


Fig. 1.— The 2006-2007 light curve of VX Hydrae. Data were normalized to the photometric mean light prior to Fourier analysis. Times are days of HJD relative to HJD 2453000.

Table 1. OBSERVER TABLE

Observer	location	time zone	number of obs 2006	number of obs 2007	telescope
N. Butterworth	Townsville, QLD	UTC+10	726	—	0.2-m, SBIG ST7e
S. Dvorak	Clermont, FL	UTC-5	3219	225	0.25-m, SBIG ST9XE
H.S. Gerner	New Berlin, WI	UTC-6	457	—	0.25-m, SBIG ST9E
R. Poklar	Tucson, AZ	UTC-7	836	1203	0.2-m, SBIG ST9E
G. Samolyk	New Berlin, WI	UTC-6	408	953	0.25-m, SBIG ST9E
G. Samolyk	Big Bend, TX	UTC-6	—	616	0.25-m, SBIG ST9XE
Annual Total			5646	2997	

Note. — Annual totals include all observations submitted; approximately 150 observations were not used in the final light curve. The “2007” data set actually began on 2006 December 20 UT.

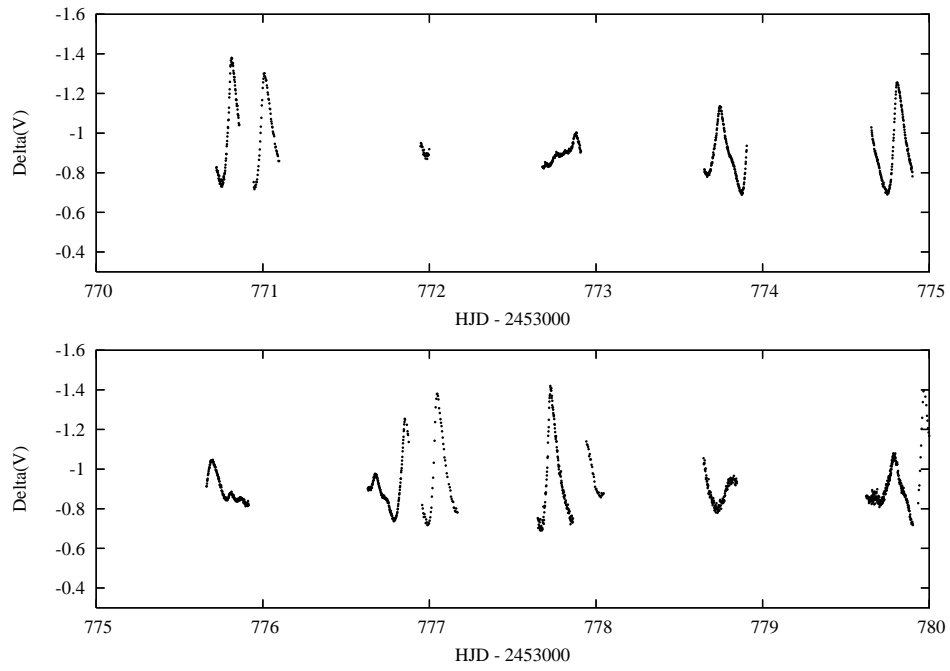


Fig. 2.— Ten days of coverage for VX Hya. The average photometric error per point is less than 10 mmag, and often 5 mmag or less. Data were collected by four observers in the United States and one in Australia; at least two days have more than 16 hours of photometry.

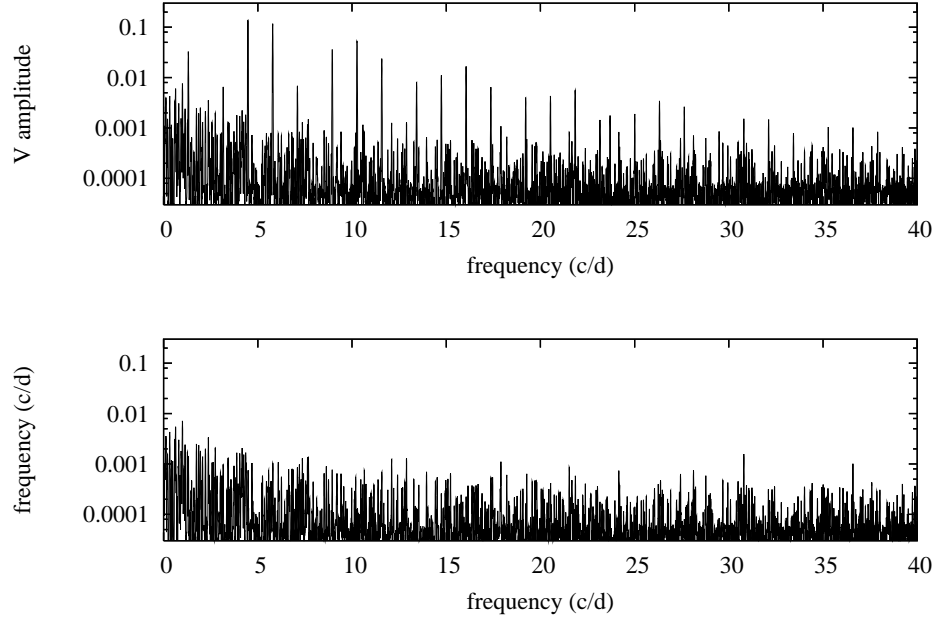


Fig. 3.— Original Fourier spectrum (top) and prewhitened spectrum (bottom) of the 2006 data set. Note that the amplitude scale is logarithmic to clearly show the significance of the low-amplitude peaks. Thirty frequencies were detected in the 2006 data set having amplitude significantly above the noise level. Of these 30, 25 are also observed in the 2007 data set. The prewhitened spectrum shows no other significant peaks, indicating that all of the periodic variations in VX Hya are due to the two radial modes and their linear combination frequencies.

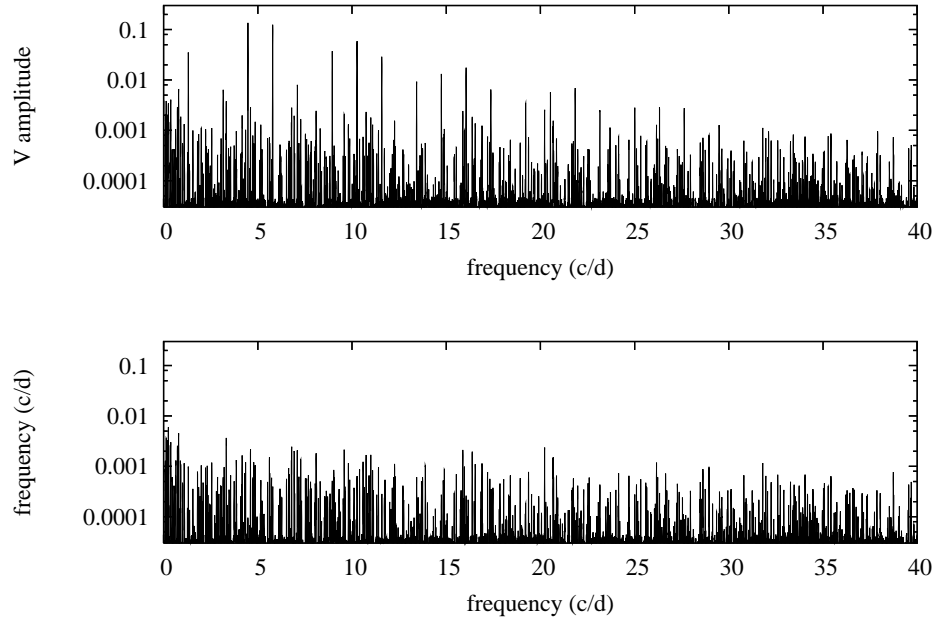


Fig. 4.— Original Fourier spectrum (top) and prewhitened spectrum (bottom) of the 2007 data set. Twenty-six frequencies were detected in the 2007 data set having amplitude significantly above the noise level. Of these 26, 25 are also observed in the 2006 data set. As with the 2006 data, no other significant peaks are observed following prewhitening.

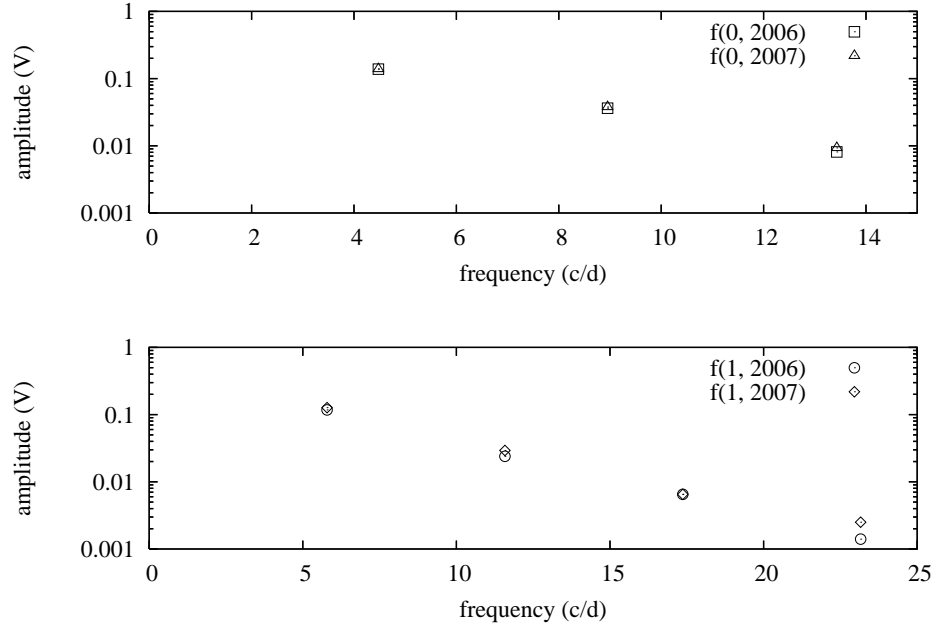


Fig. 5.— Fourier harmonic amplitudes for  $f_0$  (top) and  $f_1$  (bottom) showing the exponential decline in harmonic amplitude with increasing harmonic order (an exponential decline appears linear in a log-linear graph). Similar behavior is seen in other high-amplitude pulsating stars (Jurcsik et al. 2005; Chadid & Chapellier 2006). We are therefore confident that these peaks are legitimate detections and are correctly identified as Fourier harmonics.

Table 2. Frequencies, phases, and amplitudes for the 25 peaks common to both the 2006 and 2007 data sets. Phases are relative to the temporal centers of each season’s data:  $t_{0,2006} = 2453807.3515$ ;  $t_{0,2007} = 2454151.7757$ . Numbers in parentheses are the  $1\sigma$  errors in the last decimal place of the given number.

freq. (2006) (c/d)	V amp. (2006) (mag)	phase (2006) (radians)	freq. (2007) (c/d)	V amp. (2007) (mag)	phase (2007) (radians)	$\Delta(A)_{2007-2006}$ (mag)	ident. $i, j$
4.47650(2)	0.1384(4)	0.137(5)	4.47658(2)	0.1391(7)	−1.0961(8)	0.0007(6)	+1, +0
5.78981(2)	0.1176(4)	−0.549(5)	5.78983(3)	0.1271(7)	0.5032(9)	0.0095(6)	+0, +1
10.26629(5)	0.0531(4)	−2.673(1)	10.26644(6)	0.0591(7)	−2.790(2)	0.0060(6)	+1, +1
8.95295(7)	0.0363(4)	−1.917(2)	8.95295(9)	0.0378(7)	1.935(3)	0.0015(6)	+2, +0
1.31386(8)	0.0328(4)	2.439(2)	1.31309(9)	0.0352(7)	−1.659(3)	0.0024(6)	−1, +1
11.5795(1)	0.0239(4)	−2.976(3)	11.5798(1)	0.0293(7)	−0.918(4)	0.0054(6)	+0, +2
16.0561(1)	0.0168(4)	0.522(4)	16.0564(2)	0.0177(7)	1.557(6)	0.0009(6)	+1, +2
14.7428(2)	0.0110(4)	1.852(6)	14.7429(2)	0.0134(7)	0.388(9)	0.0024(6)	+2, +1
13.4293(3)	0.0081(4)	2.389(8)	13.4296(3)	0.0093(7)	−1.24(1)	0.0012(6)	+3, +0
7.1029(4)	0.0069(4)	−0.969(9)	7.1017(4)	0.0080(7)	2.47(1)	0.0011(6)	−1, +2
3.1641(4)	0.0066(4)	1.687(9)	3.1641(5)	0.0066(7)	−2.06(2)	0.0000(6)	+2, −1
17.3699(4)	0.0065(4)	0.82(1)	17.3692(5)	0.0065(7)	−2.61(2)	0.0000(6)	+0, +3
21.8448(4)	0.0056(4)	−2.11(1)	21.8466(5)	0.0071(7)	0.02(2)	0.0015(6)	+1, +3
20.5330(6)	0.0043(4)	−1.19(1)	20.533(6)	0.0057(7)	−1.47(2)	0.0014(6)	+2, +2
19.2196(6)	0.0040(4)	−0.02(2)	19.2191(9)	0.0036(7)	−2.82(3)	−0.0004(6)	+3, +1
26.3216(7)	0.0035(4)	1.76(2)	26.324(1)	0.0029(7)	2.63(4)	−0.0006(6)	+2, +3
27.6368(9)	0.0027(4)	1.54(2)	27.635(1)	0.0028(7)	−1.65(4)	0.0001(6)	+1, +4
25.009(1)	0.0019(4)	2.95(3)	25.010(1)	0.0029(7)	1.31(4)	0.0010(6)	+3, +2
23.697(1)	0.0018(4)	−1.99(3)	23.695(3)	0.0011(7)	0.0(1)	−0.0007(6)	+4, +1
32.115(2)	0.0015(4)	−0.55(4)	32.111(3)	0.0010(7)	1.1(1)	−0.0005(6)	+2, +4
23.162(2)	0.0014(4)	−1.63(4)	23.159(1)	0.0025(7)	2.20(5)	0.0011(6)	+0, +4
35.279(2)	0.0010(4)	−2.06(6)	35.277(4)	0.0008(7)	2.2(1)	−0.0002(6)	+4, +3
29.485(3)	0.0009(4)	0.23(7)	29.486(3)	0.0013(7)	−2.00(9)	0.0004(6)	+4, +2
37.902(3)	0.0008(4)	2.70(8)	37.900(3)	0.0010(7)	−0.2(1)	0.0002(6)	+2, +5
33.432(3)	0.0008(4)	−0.12(8)	33.423(4)	0.0008(7)	3.1(1)	0.0000(6)	+1, +5